conduits that are more than 6m (20 ft) underground, the sampler pump is installed in a JIC waterproof box within 3m (10 ft) of the minimum overflow level. The pump pushes the sample to an above-ground location where the sample bottles are stored in a refrigerator. A relay which accepts the 4-20 ma signal from the flowmeter probe at each outfall is used to start the sampler automatically when the signal increases to approximately 4.2 ma. This is intended to coordinate the starting of the sampler with the first measurable amount of overflow. Samples are collected at 15 minute intervals unless the pumping distance is such that suction and purge times of greater than 15 minutes are necessary.

RECAPITULATION

In fairness to present day equipment, it must be pointed out that some of the above cited complaints stem from equipment designs of up to six years ago, and many commercial manufacturers, properly benefitting from field experience, have modified or otherwise improved their products' performance. The would-be purchaser of commercial automatic samplers today, however, should keep in mind the design deficiencies that led to the foregoing complaints when selecting a particular unit for his application.

Although not in the storm and combined sewer area, the field experience of the EPA Region VII Surveillance and Analysis Division recently reported (8) must be mentioned. Their experience, involving over 90,000 hours use of some 50 commercial automatic liquid samplers of 15 makes and models, has indicated that the mean sampler failure rate is approximately 16 percent with a range of 4 percent to 40 percent among types. They have found that the ability of an experienced team to gather a complete 24-hour composite sample is approximately 80 percent. When one factors in the possibility of mistakes in installation, variations in personnel expertise, excessive changes in lift, surcharging, and winter operation, it is small wonder that projects on which more than 50 or 60 percent of the desired data were successfully gathered using automatic samplers were, until recently, in the minority.

In their report (8) the writers summarize a long and extensive history of field experience with portable automatic liquid samplers, give operational problems encountered on a make and model basis, offer valuable tips on the installation and operation of sampling equipment, and present comparison data of different commercial units used on a side-by-side basis. They noted variations in data traceable to differences in equipment performance ranging (at best) from ±9 to 24 percent. In some instances differences in total suspended solids levels were over 300 percent. Such findings re-emphasize the need for careful equipment selection if flows high in suspended solids are to be sampled.

In recently completed controlled laboratory testing supported by the EPA (32), four different types of automatic samplers manufactured by four different companies were tested on a side-by-side basis with known flow parameters (particle density, size, and concentration and flow velocity and depth). As a typical example, in a flow mixture of water and a synthetic organic suspended solid (specific gravity = 1.06, grain size 10 mesh $\geq$ d $\geq$ 12 mesh) at a 300 ppm concentration and a velocity of 0.6 m/s (2 fps), analysis of samples taken by the commercial samplers indicated that sample representativeness varied from 25 percent low to over 400 percent high. Similar results were obtained at a concentration of 600 ppm, and the results are especially significant because these conditions should allow for "easy" sampling. With finer (120 mesh $\geq$ d $\geq$ 140 mesh), heavier (specific gravity = 2.65) suspended solids, the performance of commercial samplers was even poorer - the concentration generally being grossly understated.

The commercial sampler testing discussed above, although just scratching the surface, clearly points out the need for more controlled laboratory testing and for the development of performance specifications for automatic wastewater samplers as well as standard testing and acceptance procedures. Only then will we be able to speak authoritatively about the ability of an automatic sampler to characterize a wastewater stream in a pollutant mass discharge sense.

SECTION IX

STATE-OF-THE-ART ASSESSMENT

As can be noted from a review of the preceding sections, despite the plethora of automatic liquid sampling equipment that is available today, none is eminently suited for a storm and/or combined sewer application. An assessment of the current state-of-the-art from the technological viewpoint is in order to indicate where and how improvements can be made and to give design guides for the development of new automatic samplers. The material is arranged in subsections which deal with each of the basic sampler functions, and the emphasis is on technical considerations to assure satisfactory execution of each function. The functions are interrelated, however, and the designer must use a systems approach in his synthesis and analysis activities.

SAMPLER INTAKE ASSESSMENT

The sample intake of many commercially available automatic liquid samplers is often only the end of a plastic suction tube, and the user is left to his own ingenuity and devices if he desires to do anything other than simply dangle the tube in the stream to be sampled. In the following paragraphs we wish to examine the functions of a sampler intake that is intended to be used in a storm or combined sewer application and the design considerations that arise therefrom.

Pollutant Variability

A general discussion of the character of storm and combined sewage is given in section III where the variability of pollutant concentration is also treated. We wish to consider the latter factor here in somewhat more detail. Let us consider first some empirical data from (25). In the study, a special pressurized circulating loop was assembled containing a 25.4 cm (10 in.) square test section some 4.6m (15 ft) long. Careful measurements of the velocity contours were made and near uniformity was observed. From figure 23, which shows such velocity contours for a nominal 1.5 m/s (5 fps) velocity flow, it can be seen that the velocity 1.3 cm (0.5 in.) from the wall exceeds 1.4 m/s (4.5 fps) everywhere except near the corners. Since the variability of a pollutant will be a function of velocity variations (among other factors), it is of interest to note the horizontal and vertical variations of sediment distribution observed experimentally in this test section with its very small velocity variation.

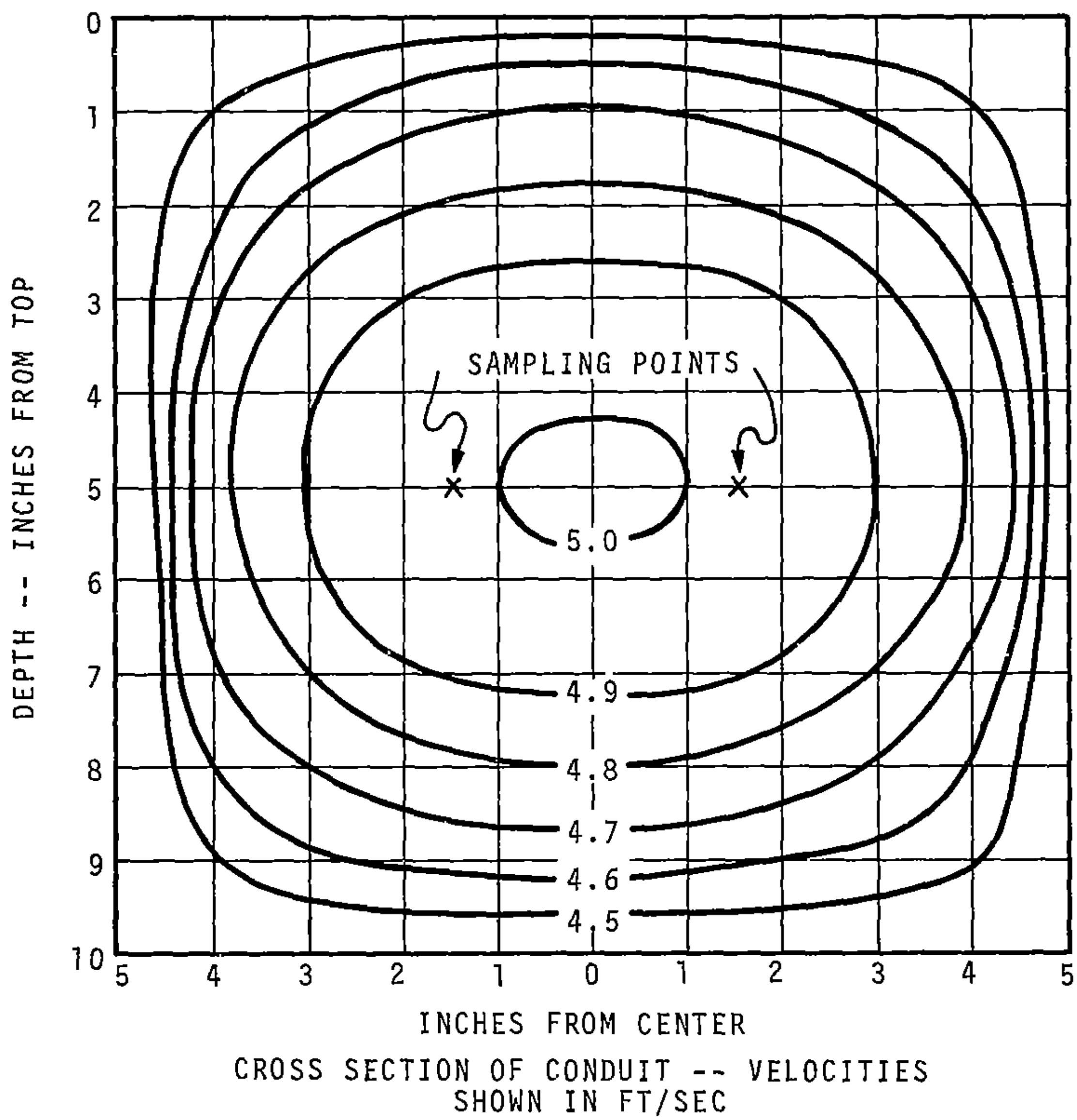


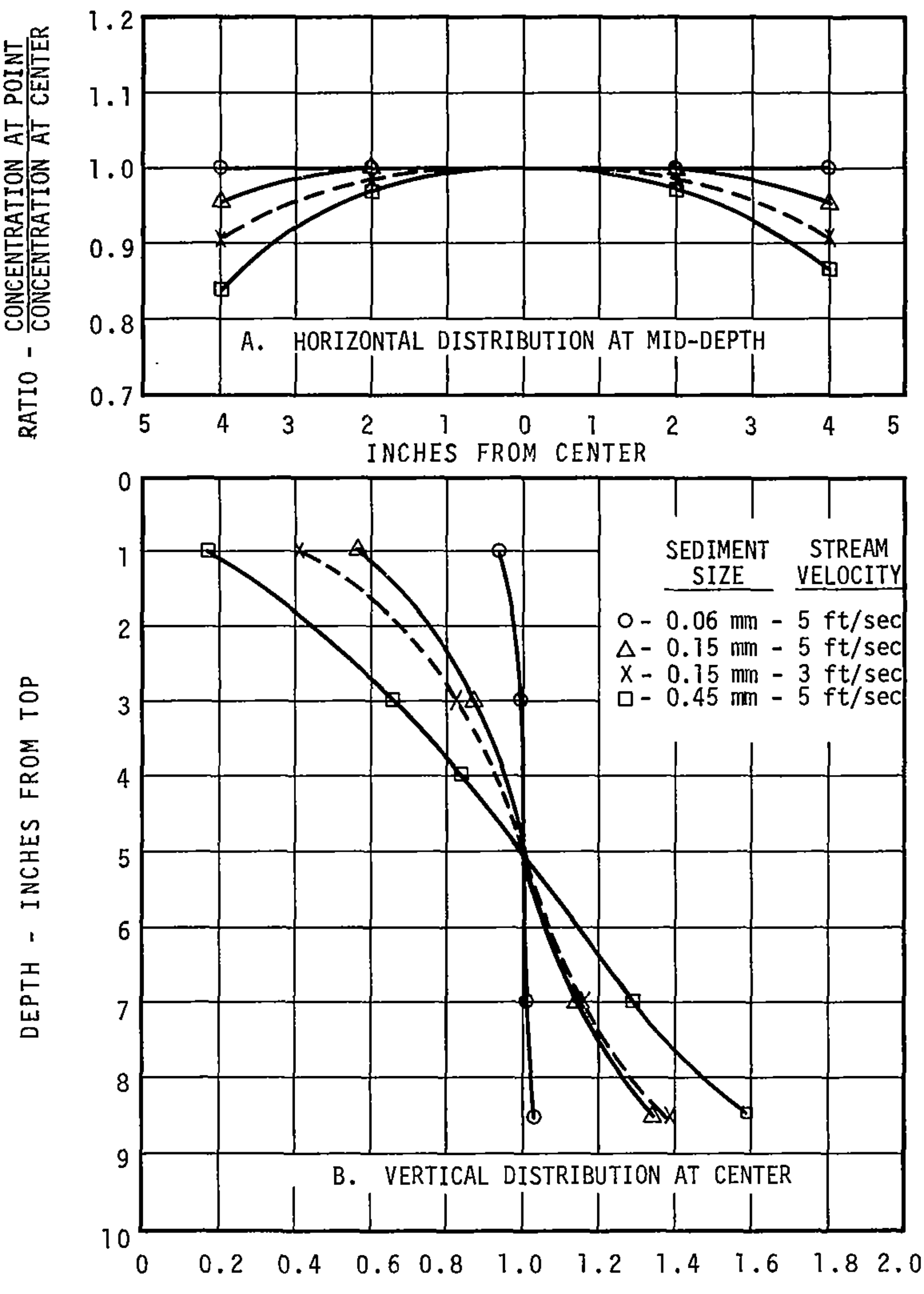
Figure 23. Velocity Contours at Sampling Station*

* Taken from reference 24.

Four readily available commercial sands, differing principally in size, were used in the study. They are referred to by mean particle size (50 percent finer by weight) as 0.45 mm, 0.15 mm, 0.06 mm and 0.01 mm. Observed sediment distribution for the three coarsest sands are indicated in figure 24. For all practical purposes the 0.01 mm sand was uniformly distributed. It should be noted here that the vertical variation is probably enhanced due to the design of the test loop, which would tend to enhance concentrations of heavier particles to the outside (the bottom of the test section in this case) due to the action of centrifugal forces. Observations made in (7) indicate this effect rather effectively. In their test set-up a 2.4m (8 ft.) wide flume was narrowed to a 46 cm (18 in.) test section by placing an insert in the flume bed along the wall opposite to that from which samples were to be extracted. Although the reduction in width occurred some 11m (36 ft.) upstream of the sampler inlet, for the 0.45 mm sand used in the investigation, concentrations at 2.5 cm (1 in.) from the wall were found to be two to four times greater than at 7.6 cm (3 in.) from the wall. Similar but less pronounced horizontal concentration gradients were observed for the finer sands as well.

The observation was made in (7) that, in addition to variations in sediment concentration within the cross-section at a given time, the sediment concentration at any point in the cross-section was highly variable with respect to time, especially for the coarser sediments (0.45 mm). This observation was also made in (24) where data are presented on concentration variation with respect to time as a function of sampling interval. The concentration of successive 20-second samples was found to vary over a range of 37 percent of the mean, and the concentration of successive 60-second samples varied over a range of 10.5 percent. Such variations arise from the natural turbulence of the flow as would be encountered in an actual sewer and from the non-uniform nature of re-circulated flows in test loops which is peculiar to such laboratory simulations.

So far we have focused our attention on relatively heavy (specific gravity approximately 2.65) solids and their distribution in a flow. For the lighter organic solids with specific gravities near unity, the particle distribution will be more nearly uniform in a turbulent flow. It would appear that one can expect a reasonable degree of uniformity in the distribution of particles which fall in the Stokes' Law range of settling velocities, i.e., for values of the external Reynolds' number less than unity. If one describes



* Taken from reference 24.

Figure 24. Sediment Distribution at Sampling Station*

a particle in terms of its hydraulic size W, defined as the velocity of uniform fall in a fluid at rest, Stokes' Law can be written as

$$W = gd^2 \ (s.g.-1)/18\nu \qquad (1)$$

where d is mean particle diameter, s.g. is the specific gravity of the particle material, ν is the kinematic viscosity of the fluid, and g is the acceleration of gravity. The external Reynolds' number (so called because the linear dimension upon which it is based is a particle dimension rather than a flow dimension) can be expressed as

$$Re = Wd/\nu \qquad (2)$$

Combining equations (1) and (2) we can express the range of validity of Stokes' Law as

$$Re = gd^3 \ (s.g.-1)/18\nu^2 < 1 \qquad (3)$$

If one considers water at 15.6°C (60°F) as the fluid (ν=1.217 x10^{-5} ft^2/sec), a plot of equation (3) over the range of interest is given in figure 25. Here it can be noted that, within the range of Stokes' Law, the maximum particle diameter for sand with a specific gravity of 2.65 is less than 0.1 mm while for organic particles with a specific gravity of 1.05 it is about 0.3 mm.

Since the kinematic viscosity of water is temperature dependent, the Stokes' Law particle diameter limit will also be a function of temperature. A typical plot of this variation is given in figure 26 for sand with a specific gravity of 2.65 and Re=1. Here it can be noted that a decrease in water temperature from the upper eighties to the mid-forties results in a 50 percent increase in the maximum particle diameter.

Sampler Intake Functions

The operational function of a sampler intake is to reliably allow gathering a representative sample from the flow stream in question. Its reliability is measured in terms of freedom from plugging or clogging to the degree that sampler operation is affected and invulnerability to physical damage due to large objects in the flow. It is also desirable, from the viewpoint of sewer operation, that the sampler intake offer a minimum obstruction to the flow in order to help prevent blockage of the entire sewer pipe by lodged debris, etc.

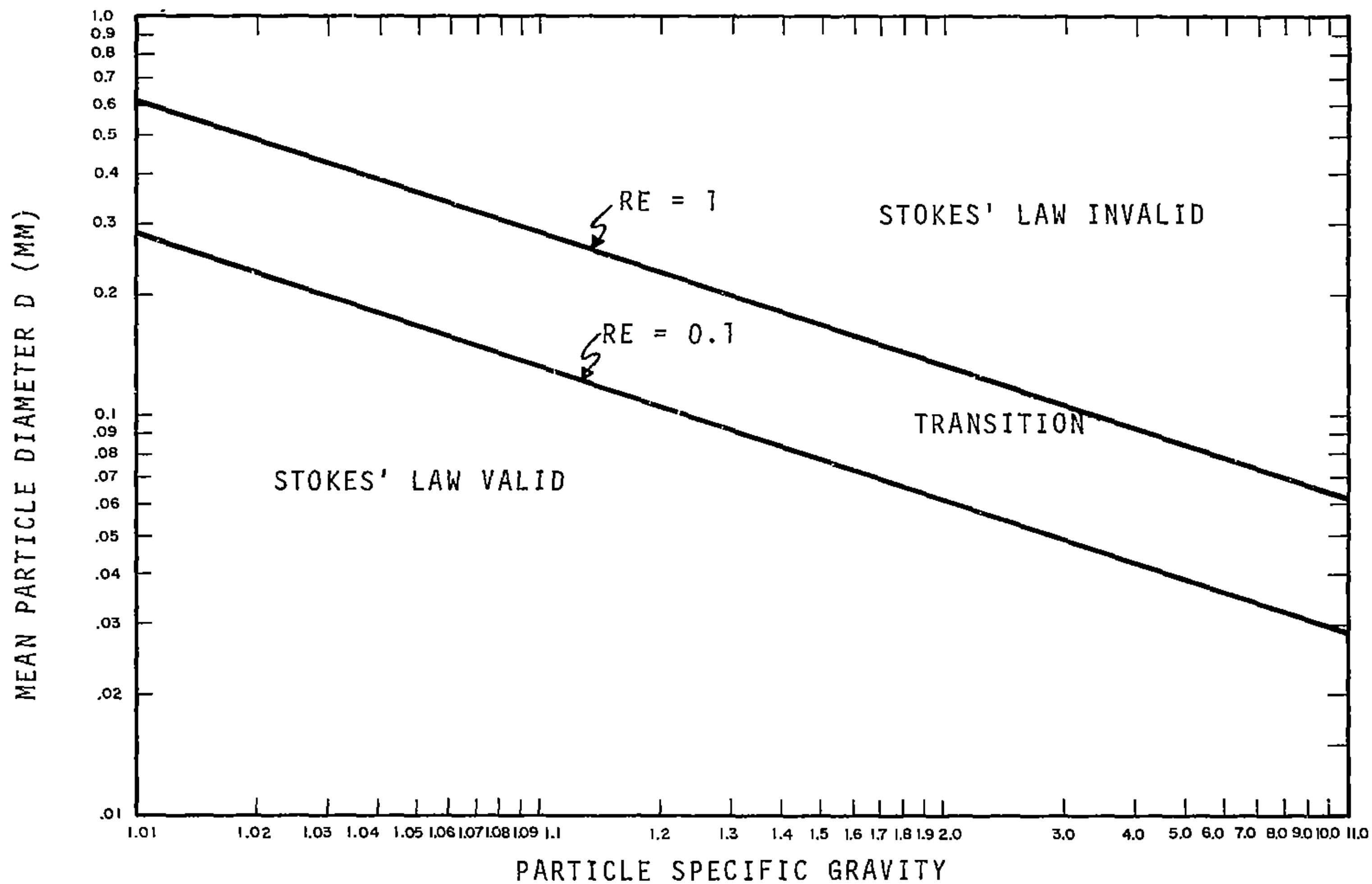


Figure 25. Region of Validity of Stokes' Law

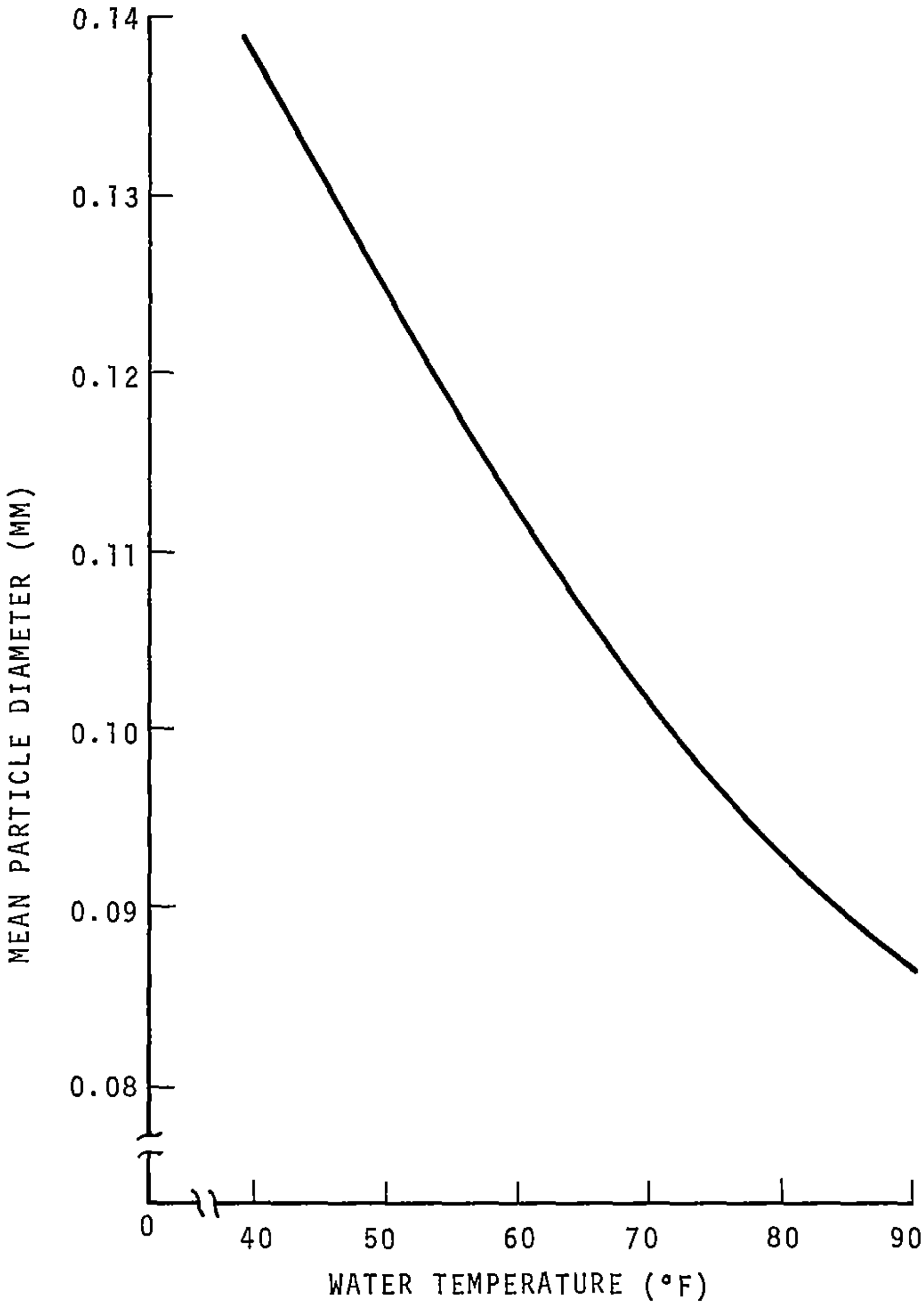
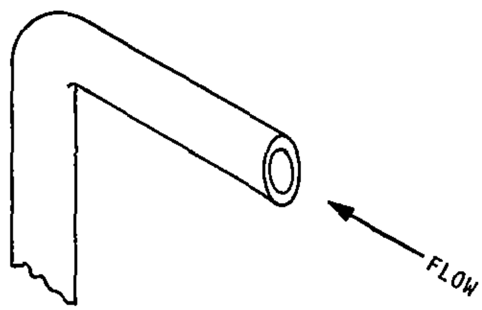


Figure 26. Effect of Temperature on Maximum Particle Size (Re=1)

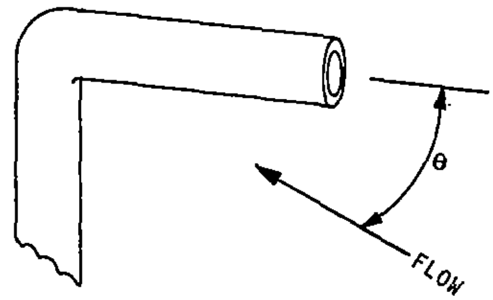
Let us first consider the ability of the intake to gather a representative sample of dense suspended solids in the sediment range, say up to 0.5 mm with specific gravity of 2.65. The results of a rather thorough examination of relatively small diameter intake probes, 0.63 and 0.32 cm (1/4 and 1/8 in.) I.D., are given in (25). The argument is developed that, for a nozzle pointing directly upstream into the flow (figure 27a), the most representative sample of a fluid/suspended-solids mixture will be obtained when the sampling velocity is equal to the flow velocity at the sampling point. Using this as the reference criteria, investigations were conducted to determine the effects of a) deviations from the normal sampling rate, b) deviations from the straight-into-flow position of the probe, c) deviations in size and shape of the probe, and d) disturbance of sample by nozzle appurtenances. The effect of the sampling velocity on the representativeness of the sample is indicated in figure 28 which presents the results for 0.45 mm and 0.06 mm sand. For the latter size, which falls within the Stokes' Law range, less than ±4 percent error in concentration was observed over sampling velocities ranging from 0.4 to 4 times the stream velocity. For the 0.45 mm particles, the error at a relative sampling rate of 0.4 was +45 percent, and at a relative sampling rate of 4 the error was -25 percent.

For probe orientations up to 20° to either side of head-on (figure 27b), no appreciable errors in concentration were observed. Similarly, introduction of 0.381 and 0.952 cm (0.150- and 0.375-in.) probes showed comparatively little effect on the representativeness of the sample. The probe inlet geometry, i.e., beveled inside, beveled outside, or rounded edge, also showed little effect on the representativeness of the sample, when compared to the standard probe. Finally, in instances where a sampler body or other appurtenance exists, the probe should be extended a short distance upstream if a representative sample is to be collected. In summary, it was found that for any sampler intake facing into the stream, the relative sampling rate is the primary factor to be controlled.

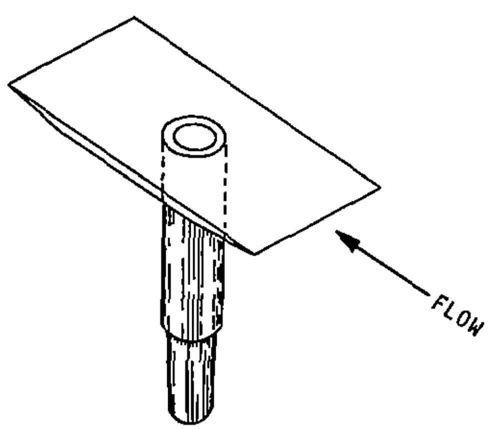
Tests were also run with the sampling intake probes in the vertical position (figure 27c) to determine the effect such an orientation had upon the representativeness of the sample. With such intakes, the sample entering them must undergo a 90° change of direction, and consequently there is a tendency for segregation and loss of sediment to take place. Tests were run with the standard probe, a 0.63 cm (1/4 in.) diameter orifice in the center of a 2.5 x 5 cm (1 x 2 in.) plate oriented so that its longest dimension was in the direction of flow, and with an orifice in a crowned (mushroom shaped)



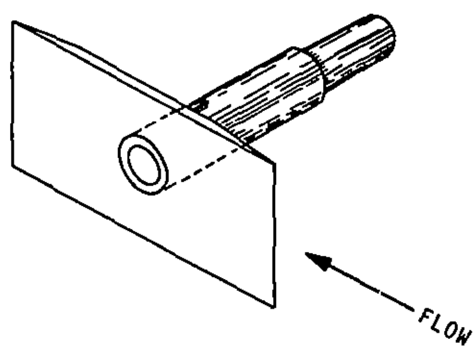
27a. Normal Orientation Directly Into Flow



27b. Orientation at an Angle to Head-on



27c. Vertical Orientation (0°) - Orifice in Flat Plate



27d. Horizontal Orientation (90°) - Orifice in Flat Plate

Figure 27. Sampler Intake Orientations Tested

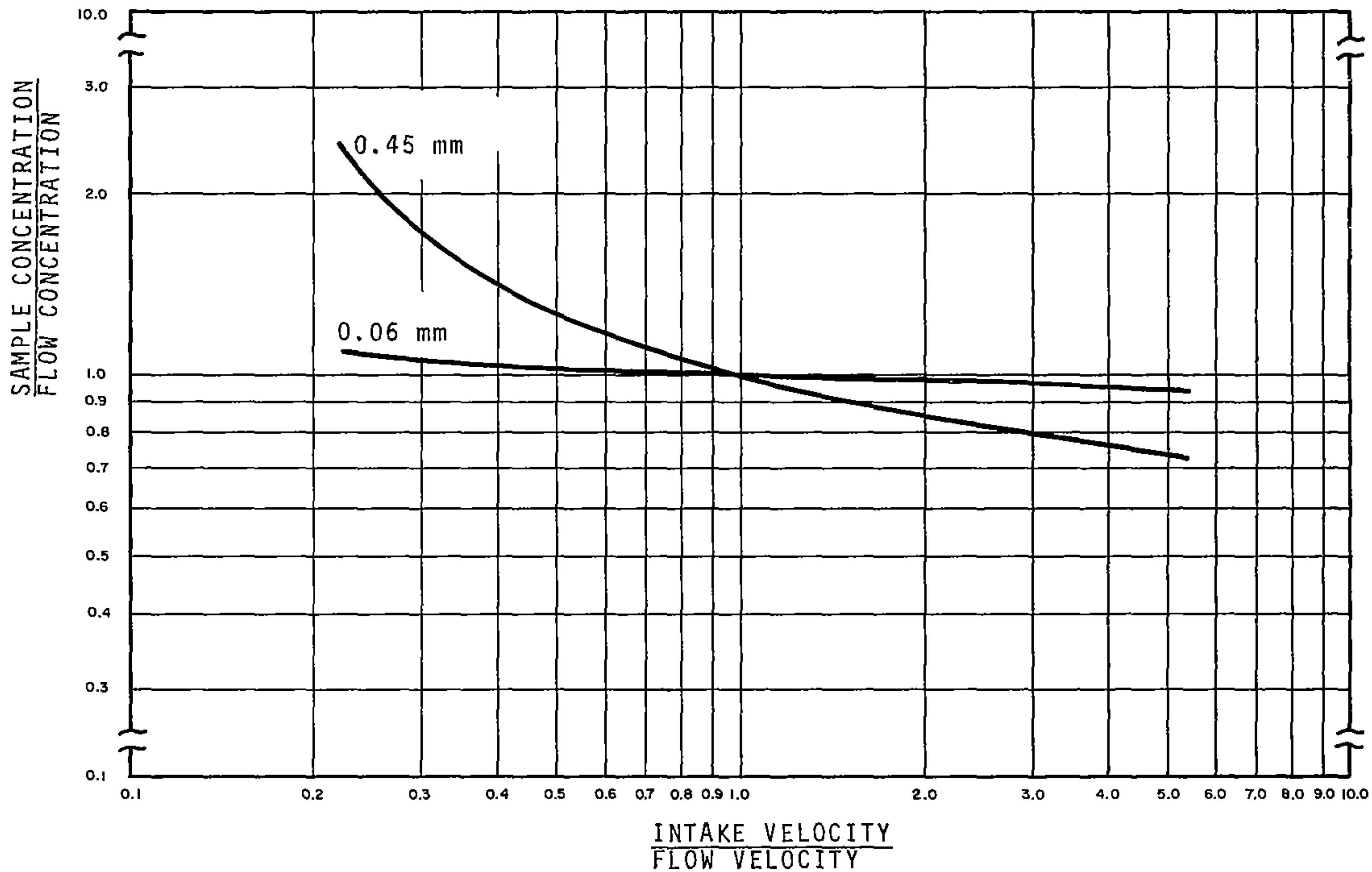


Figure 28. Effect of Sampling Velocity on Representativeness of Suspended Solids*

* Data from reference 24.

flat plate 3.2 x 5 cm (1.25 x 2 in.). The results all showed negative errors in concentration, increasing with particle size and increasing with intake velocities less than the stream rate but nearly constant for intake velocities higher than the stream rate.

Since the smallest errors were found for the orifices in the flat and mushroom shaped plates (whose performances were nearly identical for intake velocities greater than one-half the stream velocity), it was decided to investigate the effect of lateral orientation, i.e., to rotate the plate 90° so that it might represent an orifice in the side of a conduit rather than in the bottom (figure 27d). The results for 0.15 mm sand are presented in figure 29. It can be noted that while the side orientation caused greater errors (as was to be expected), these errors approached the nearly constant error of the 0° orientation (figure 27c) as the relative sampling rate was increased above unity.

The work reported in (7) was a laboratory investigation of pumping sampler intakes. Nine basic intake configurations, all representing an orifice of some type in the side wall of the flume, were examined. They included 1.3, 1.9, 2.5, and 3.8 cm (0.5, 0.75, 1.0, and 1.5 in.) diameter holes with square edges, 1.9 cm (0.75 in.) diameter holes with 0.32 and 0.63 cm (0.125 and 0.25 in.) radii, 1.3 x 2.5 cm (0.5 x 1 in.) ovals, one oriented vertically and the other horizontally, and a 1.9 cm (0.75 in.) diameter hole with a 5 cm (2 in.) wide shelf just under it. Sand sizes of 0.10 mm and 0.45 mm were used in the study.

Reference samples were taken with a probe located near the wall and pointing into the direction of the flow. The reference sample intake velocity was equal to the stream velocity. The primary measurement was sampling efficiency, the ratio of the sediment concentration in the test sample to that of the reference sample computed for a point 1.3 cm (1/2 in.) from the wall. The reference sample was taken just before and just after the test sample was gathered. Although the data exhibited considerable scatter, several conclusions were drawn. With regard to the intake velocity, greater than 0.9 m/s (3 fps) is generally desirable and, for sands coarser than 0.2 mm, an intake velocity equal to or greater than the stream velocity is desirable. With regard to intake configuration, for intake velocities greater than about 0.9 m/s (3 fps), the sampling efficiencies showed little effect of size of intake (range of 1.3 to 3.8 cm diameter), of rounding the intake edges, or of shape and orientation of the axis of the oval intake. Sampling efficiency was found to decrease with increasing particle size above 0.10 mm for all intakes tested. Finally,

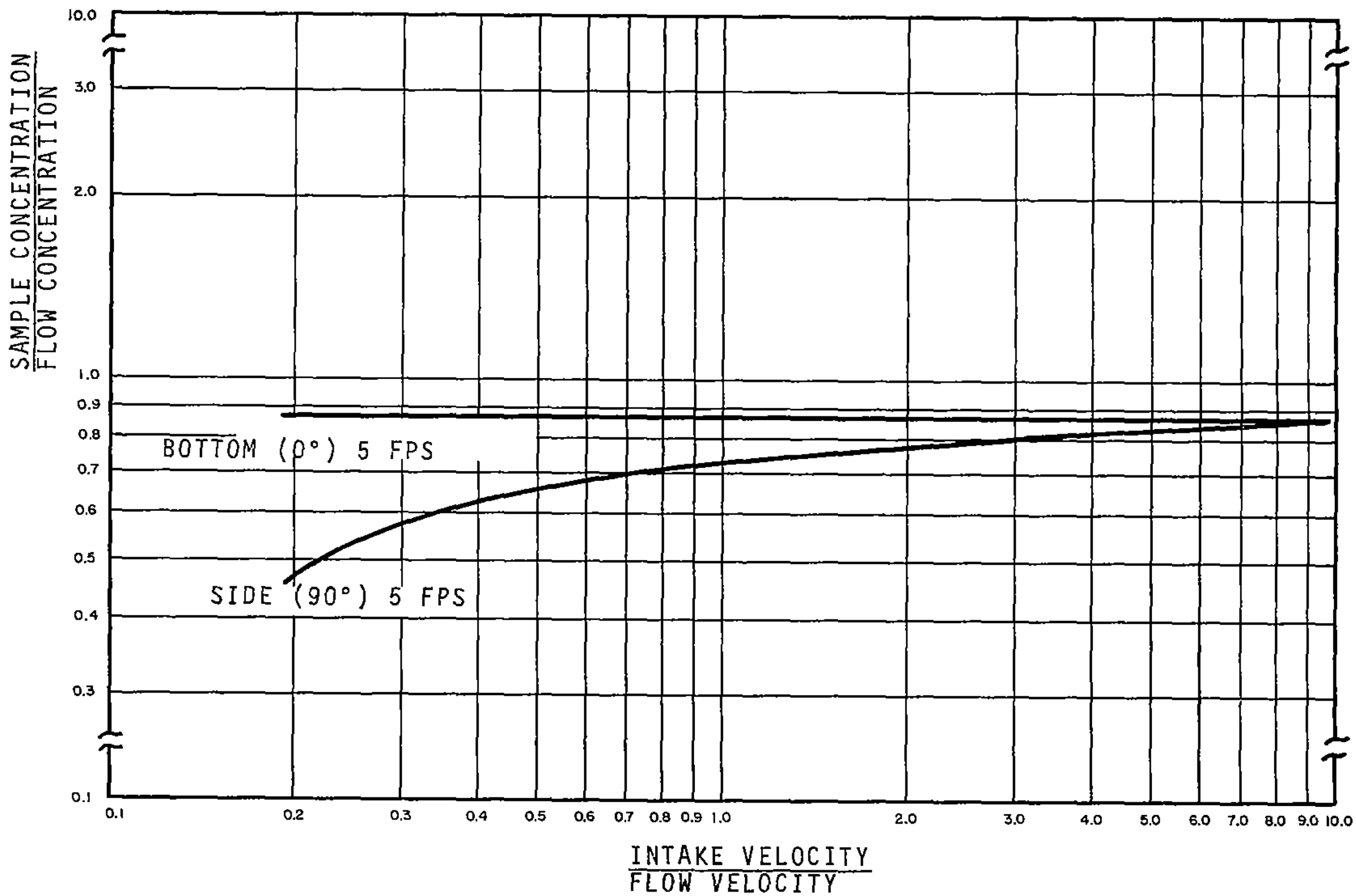


Figure 29. Effect of Lateral Orientation of Sample Intake*

* Data taken from reference 25.

although the shelf intake showed somewhat higher sampling efficiency for coarse particles and high stream rates, its performance was very erratic over the entire range of test parameters.

Similar observations were made in field tests with river water samples at St. Paul and Dunning, Nebraska, reported in (26). In addition to the "standard" intake which was a flush mounted 2.5 cm (1 in.) pipe coupling, alternate intakes included 2.5 x 5 cm (1 x 2 in.) and 2.5 x 23 cm (1 x 9 in.) nipples; 2.5 x 23 cm (1 x 9 in.) nipple with a 0.32 cm (1/8 in.) thick steel plate 36 cm (14 in.) high and 43 cm (17 in.) wide at its end; and a 2.5 cm (1 in.) street elbow with a 2.5 x 5 cm (1 x 2 in.) nipple oriented down, into the flow and up. It was concluded that the standard intake was as good as any in terms of sampling efficiency and was therefore preferable since it offered no obstruction to the flow and was therefore less vulnerable to damage by debris. The sediment being sampled was rather fine; in high flows 88 percent was finer than 0.062 mm and 100 percent was finer than 0.50 mm.

To summarize the foregoing as it relates to the sampler intake function of gathering a representative sample we note the following:

1) It becomes difficult to obtain a one-to-one representation, especially for inlets at 90° to the flow, for large, heavy suspended solids.

2) For particles that fall within the Stokes' Law range, consistent, representative samples can be obtained.

3) The geometry of the sampler intake has little effect on the representativeness of the sample.

4) The sample intake velocity should equal or exceed the velocity of the stream being sampled.

Sampler Intake Design

The foregoing suggest certain directions that the design of a sampler intake for storm and combined sewer flows should take. At the outset, it appears unwise to attempt to sample suspended solids that fall much outside the Stokes' Law range. A realistic maximum size for sand with specific gravity of 2.65 would appear to be around 0.1 mm to 0.2 mm.

High sample intake velocities will be required, perhaps in excess of 3 m/s (10 fps), if the sample is to be representative. Although the flow may be nearly homogeneous, except for very coarse solids and large floatables, more than one sample intake is desirable for reliability of operation as well as insurance against some unforeseen gradient in the pollutant. In view of the changing water levels in the conduit with changing flows, the changing velocity gradients within the flows, and the possibility of changing pollutant gradients not only with respect to these but also with type of pollutant; not even a dynamically adaptive sampler intake can be designed to gather a sample that is completely representative in every respect at the same time.

In order to better illustrate this point, let us consider a round pipe of radius R containing a flow at depth d and an arbitrary vertical concentration gradient of some pollutant.

Locate the origin of a cartesian coordinate system at the invert with the y axis positive upwards. We now assume that the pollutant concentration gradient can be expressed as a polynomial in y, i.e.,

$$p = \sum_n a_n y^n \tag{4}$$

The expression for the amount of pollutant in an arbitrary cross-sectional zone (say between depths y_1 and y_2) is

$$P = \iint \sum_n a_n y^n dxdy = 2 \int_{y_1}^{y_2} \sum_n a_n y^n \sqrt{2yR-y^2}\, dy \tag{5}$$

If one sets $P = \sum_n P_n$ the first few terms are;

$$P_o = a_o \left\{ \left[(y_2-R)\sqrt{2Ry_2-y_2{}^2} - (y_1-R)\sqrt{2Ry_1-y_1{}^2} \right] + R^2 \left[\sin^{-1}(y_2/R-1) - \sin^{-1}(y_1/R-1) \right] \right\} \tag{6}$$

$$P_1 = 2a_1 \left\{ -\frac{1}{3}\left(2Ry_2-y_2{}^2\right)^{3/2} + \frac{1}{3}\left(2Ry_1-y_1{}^2\right)^{3/2} + \frac{RP_o}{2a_o} \right\} \tag{7}$$

$$P_2 = 2a_2\left\{y_2 - \frac{5}{12}R\left(2Ry_2-y_2^{\ 2}\right)^{3/2} - y_1 + \frac{5}{12}R\left(2Ry_1-y_1^{\ 2}\right)^{3/2} + \frac{5R^2P_o}{8a_o}\right\} \tag{8}$$

etc.

Using such a formulation one can obtain the values of y which divide the flow cross-section up into some number of zones each of which contains an equal amount of pollutant; let us designate them as $y_1, y_2, \ldots, y_m$. If one extracts a sample from the center of each zone, one can argue that its representativeness will be quite good, especially for large values of m. Unless the samples extracted from each zone are kept discrete, which would result in an inordinately large number of samples, the quantity of sample gathered from each inlet must be varied in accordance with the velocity gradient if the composite sample is to be representative in a mass transport sense. For a different concentration gradient p^1, one will obtain new values $y_1^{\ 1}, y_2^{\ 1}, \ldots, y_m^{\ 1}$ and hence different port locations and different quantities of sample required even for the same flow depth.

In view of the over-riding design mandate that simplicity maximizes probability of success, it becomes immediately apparent that the equipment sophistication implied by the foregoing would doom the design to operational failure if such a course were to be attempted. In the absence of some consideration arising from the particular installation site, a regular distribution of sampling intakes across the flow, each operating at the same velocity, would appear to suffice. Since the intakes should be as non-invasive as possible in order to minimize the obstruction to the flow and hence the possibility of sewer line blockage, it seems desirable to locate them around the periphery of the conduit.

GATHERING METHOD ASSESSMENT

As was noted earlier, three basic sample gathering methods or categories were identified; mechanical, suction lift, and forced flow. Several different commercial samplers using each method are available today. The sample lift requirements of the particular site often play a determining role in the gathering method to be employed. Some mechanical units were specifically designed for lifts to 61m (200 ft.). The penalty that one must trade-off in selecting a mechanical gathering unit is principally the necessity for some obstruction to the flow, at least while the sample is being taken. The tendency for exposed mechanisms to foul, together with the added vulnerability of many moving parts, means that successful operation will require regular, periodic inspection, cleaning, and maintenance.

Forced flow from a submersible pump also necessarily results in an obstruction to the flow. Pump malfunction and clogging, especially in the smaller sizes often used in samplers, remains a distinct possibility and, because of their location in the flow stream itself, maintenance is more difficult to perform than on above-ground or easily removable units. Pneumatic ejection is employed by several manufacturers, the gas source being either a compressor or bottled refrigerant. The latter units must necessarily be of small scale to avoid an enormous appetite for the refrigerant. The advantages of explosion-proof construction and high lift capability must be weighed against low sample intake velocities and relatively small sample capacities.

Suction lift units must be designed to operate in the environment near the flow to be sampled or else their use is limited to a little over 9.1m (30 ft.) due to atmospheric pressure. The necessity to have a pump that is free from clogging has led some designers to use peristaltic tubing pumps. Most of these operate at such low flow rates, however, that the representativeness of suspended solids is questionable. Newer high-capacity peristaltic pumps are now available and should find application in larger automatic samplers. The ability of some of these pumps to operate equally well in either direction affords the capability to blow down lines and help remove blockages. Also, they offer no obstruction to the flow since the transport tubing need not be interrupted by the pump, and strings, rags, cigarette filters and the like are passed with ease. New, small capacity, progressive-capacity screw-type pumps may also find some service in samplers. With all suction lift devices a physical phenomenon must be borne in mind and accounted for if sample representativeness is to be maintained. When the pressure on a liquid (such as sewage) which contains dissolved gases is reduced, the gases will tend to pass out of solution. In so doing they will rise to the surface and entrain suspended solids in route. (In fact, this mechanism is used to treat water; even small units for aquariums are commercially available.) The result of this is that the surface layer of the liquid may be enhanced in suspended solids, and if this layer is a part of a small sample aliquot, the sample may not be at all representative. In the absence of other mitigating factors, the first flow of any suction lift sampler should therefore be returned to waste.

All in all, the suction lift gathering method appears to offer more advantages and flexibility than either of the others. The limitation on sample lift can be overcome by designing the pumping portion of the unit so that it can be separated from the rest of the sampler and thus positioned not more than 9.1m (30 ft.) above the flow to be sampled. For the majority of sites, however, even this will not be necessary.

SAMPLE TRANSPORT ASSESSMENT

The majority of the commercially available automatic samplers have fairly small line sizes in the sampling train. Such tubes, especially at 0.3 cm (1/8 in.) inside diameter and smaller, are very vulnerable to plugging, clogging due to the build-up of fats, etc. For application in a storm or combined sewer, a better minimum line size would be 0.95 to 1.3 cm (3/8 to 1/2 in.) inside diameter.

It is imperative that adequate sample flow rate be maintained throughout the sampling train in order to effectively transport the suspended solids. In horizontal runs the velocity must exceed the scour velocity, while in vertical runs the settling or fall velocity must be exceeded several times to assure adequate transport of solids in the flow.

The complexities inherent in the study of a two-phase mixture such as soil particles and water are such that rigorous analytical solutions have not yet been obtained except in certain limiting cases such as the work of Stokes cited earlier. The use of hydraulic size, which is the average rate of fall that a particle would finally attain if falling alone in quiescent distilled water of infinite extent, as a descriptor for a particle involves its volume, shape and density. It is presently considered to be the most significant measurement of particle size. However, there are no analytical relationships to allow its computation; recourse must be made to experiment. The geometric size of a particle can be based upon its projected lengths on a set of right cartesian coordinates oriented so that a is its major axis, b is its intermediate axis, and c is its minor axis. With patience and a microscope the lengths a, b, and c of a particle can be determined. Since the number of particle shapes is infinite, a system for classification is required. One put forth in (27) is the shape factor defined as:

$$SF = c/\sqrt{ab} \tag{9}$$

which approximately defines the shape in terms of three of a multitude of dimensions of an irregular particle. Of course there may be rounded, angular, smooth and rough particles all with the same shape factor.

An excellent discussion of the fundamentals of particle size analysis is given in (28). Table 5, which is taken from data presented therein, illustrates the effect of shape factor on hydraulic size for sand particles with specific gravity of 2.65 in water at 20°C. It can be noted that while a sphere with a nominal diameter of 0.2 mm will fall only about one-third faster than a similar sized particle with a shape factor of 0.3; a sphere with a nominal diameter of 4.0 mm falls over 2-1/2 times faster than a particle with SF=0.3. For curves showing temperature effects, correction tables, etc., the reader is referred to (28).

In the absence of better data, the hydraulic size of a particle can be computed from the following (29);

$$W^{3/2} = gd^{3/2}\ (s.g.-1)/11.2\sqrt{\nu} \text{ when } \begin{matrix} 1<Re<30 \\ 0.1<d<0.6 \text{ mm} \end{matrix} \tag{10}$$

$$W^{1.8} = gd^{1.2}\ (s.g.-1)/4.4\nu^{0.2} \text{ when } \begin{matrix} 30<Re<400 \\ 0.6<d<2.0 \text{ mm} \end{matrix} \tag{11}$$

$$W = 0.875\sqrt{gd(s.g.-1)} \text{ when } \begin{matrix} Re>400 \\ d>2 \text{ mm} \end{matrix} \tag{12}$$

Equation (10) is Prandtl's formula for a smooth channel, while equation (12) is the so-called square law.

The transport of solid particles by a fluid stream is an exceedingly complex phenomena and no complete theory which takes into account all of the parameters has yet been formulated. Empirical formulae exist, however, some of which have a fairly wide range of applicability. An expression for the lowest velocity at which solid particles heavier than water still do not settle out onto the bottom

TABLE 5. EFFECT OF SHAPE FACTOR ON HYDRAULIC SIZE (IN CM/SEC)*

Nominal Diameter (mm)	Shape Factors				
	0.3	0.5	0.7	0.9	Spheres
0.20	1.78	1.94	2.11	2.26	2.43
0.50	4.90	5.63	6.31	7.02	7.68
1.00	8.49	10.10	12.10	14.00	15.60
2.00	12.50	15.50	19.30	23.90	28.60
4.00	17.80	22.40	28.00	35.60	46.90

* Taken from reference 28.

of the pipe or channel has been developed by Knoroz (30) on the basis of numerous experiments carried out under his direction at the All-Union Scientific Research Institute for Hydraulic Engineering. It expresses the velocity in meters per second as

$$V = 3\left[\sqrt{gd}\ \lg \frac{R}{4d} + W\ p^{1/4} \left(\frac{R}{d}\right)^{0.4}\right] \tag{13}$$

where average values of d and W for the solids mixture are to be used; R is the hydraulic radius; and p is the consistency by weight of the mixture, i.e., in percent the expression for p is:

$$p = \frac{\gamma_m - \gamma}{\gamma_p - \gamma_m} \frac{\gamma_p}{\gamma} \tag{14}$$

where γ is the specific weight of the fluid, γ_p is the specific weight of the particles, and γ_m is the specific weight of the mixture. For a review of this and other Russian work on the flow of a two-phase mixture, see (29).

A somewhat simpler expression for the adequate self-cleaning velocity of sewers derived by Camp from experimental findings of Shields as given in (31) is:

$$V = \sqrt{6.4gd\ (s.g.-1)/f} = \frac{1.486}{n} R^{1/6} \sqrt{0.8d(s.g.-1)} \tag{15}$$

where f is the friction factor, n is Manning's roughness coefficient, and all other terms are as previously identified. Using equation (15), for example, it is seen that a velocity of 0.6 m/s (2 fps) is required to adequately transport a 0.09 mm particle with a specific gravity of 2.65 and a friction factor of 0.025. By comparison, the fall velocity of such a particle is around 0.06 m/s (0.2 fps).

In summary, the sampling train must be sized so that the smallest opening is large enough to give assurance that plugging or clogging is unlikely in view of the material being sampled. However it is not sufficient to simply make all lines large, which also reduces friction losses, without paying careful attention to the velocity of flow. For a storm or combined sewer application, minimum line sizes of 0.95 to 1.3 cm (3/8 to 1/2 in.) inside diameter and minimum velocities of 0.6 to 0.9 m/s (2 to 3 fps) would appear warranted.

SAMPLE CAPACITY AND PROTECTION ASSESSMENT

For storm and combined sewer applications, discrete sampling is generally desired. This allows characterization of the sewage throughout the time history of the storm event. If the samples are sufficiently large, manual compositing can be performed based on flow records or some other suitable weighting scheme. Although the quantity of sample required will be a function of the subsequent analyses that are to be performed, in general at least a liter, and preferably two, will be desired. An additional benefit arises because such relatively large samples are less vulnerable to errors arising from cross-contamination.

A brief look at the different types of composite samples is in order. Any scheme for collecting a composite sample is, in effect, a method for mechanically integrating to obtain average characteristics. Let us consider a given flow rate q(t) and pollutant concentration level k(t) where:

$$q \overset{d}{=} L^3T^{-1} \text{ and } k \overset{d}{=} ML^{-3} \tag{16}$$

The quantity of flow and pollutant are then:

$$Q = \int qdt \text{ and } P = \int qkdt \tag{17}$$

where:

$$Q \overset{d}{=} L^3 \text{ and } P \overset{d}{=} M \tag{18}$$

Let us consider first the simple composite, where a constant volume of fluid is added at evenly spaced time intervals. We will denote such a sample by T_cV_c, meaning time interval between successive aliquots constant and volume of aliquot constant. Let the time duration of the event in question be divided up into n elements and a subscript i be used to denote instantaneous values ($0<i\leq n$). Then the overall concentration of the simple composite sample will be:

$$K = \frac{P}{Q} \approx \frac{1}{n}\sum_{i=1}^{n} k_i \tag{19}$$

If one wishes a more representative sample, some type of proportioning must be used. This is equivalent to saying that equation (19) is a very poor scheme for numerical integration, and a higher order method is desirable. There are two fundamental approaches to obtaining better numerical integration given a fixed number of steps. One is to increase the order of the integration scheme to be used; as in going from the trapezoidal rule to Simpson's rule, for instance. The other is to vary the step size in such a way as to lengthen the steps when slopes are changing very slowly and shorten them when slopes change rapidly. Typical of the first approach are the constant time interval, variable volume (T_cV_v) proportional composites. There are two straightforward ways of accomplishing this. One is to let the aliquot volume be proportional to the instantaneous flow rate, i.e.:

$$v_i = Aq_i \tag{20}$$

and the other is to make the aliquot volume proportional to the quantity of flow that has passed since extraction of the last aliquot, i.e.:

$$v_i = B(Q_i - Q_{i-1}) = B\Delta Q_i \tag{21}$$

The respective concentrations of samples are

$$K_A = \frac{\sum_{i=1}^{n} q_i k_i}{\sum_{i=1}^{n} q_i} \text{ and } K_B = \frac{\sum_{i=1}^{n} \Delta Q_i k_i}{\sum_{i=1}^{n} \Delta Q_i} \tag{22}$$

Typical of the second approach is the variable time interval, constant volume (T_vV_c) proportional composite. Here a fixed volume aliquot is taken each time an arbitrary quantity of flow has passed (Q/n), i.e. the time is varied to give a constant ΔQ. The concentration will be:

$$K = \frac{1}{n}\sum_{i=1}^{n} k_i \tag{23}$$

It must be remembered that here the time steps are differing so that comparison of equations (23) and (19) has no meaning.

It is instructive to compare these four composite sample schemes with each other. For the purposes of this exercise let us arbitrarily set n=10 and normalize time so that $0 \leq t \leq 1$. We will examine four flow functions; q=c, q=t, q=1-t, and q=sinπt. We will also examine five concentration functions; k=1-t, k=1-t/2, k=cosπt/2, k=e^{-t}, and k=sinπt.

These selections are completely arbitrary (except for simplicity in exact integration), and the curious reader may wish to examine more typical expressions. For a storm event, the combination $q=\sin\pi t$ and $k=e^{-t}$ allows for low volume, highly polluted flow initially, with pollutant concentration falling throughout the event. However the resemblence is qualitative only, and more refined expressions could be used. For each flow/concentration combination, the exact average concentration of the flow was computed (as though the entire flow stream were diverted into a large tank for the duration of the event and then its concentration measured). The ratio of the composite sample concentration to the actual concentration so computed is presented in matrix form in table 6. The four lines in each cell represent the four types of composite samples discussed as indicated in the legend. The best overall composite for the cases examined is the T_cV_v with the volume proportional to the instantaneous flow rate q. The T_cV_v, where the volume is proportional to the flow since the last sample, and the T_vV_c gave very similar results with a slight edge to the former. However, the differences are not large for any case. This brief look at compositing merely scratches the surface, but a more definitive treatment is outside the scope of the present effort. Suffice it to say here that both flow records and a knowledge of the temporal fluctuation of pollutants, as can be obtained from discrete samples, are required in order to choose a "best" compositing scheme for a given installation.

The sample container itself should either be easy to clean or disposable. The cost of cleaning and sterilizing makes disposable containers attractive, especially if bacteriological analyses are to be performed. Although some of today's better plastics are much lighter than glass and can be autoclaved, they are not so easy to clean or inspect for cleanliness. Also the plastics will tend to scratch more easily than glass and, consequently, cleaning a well-used container can become quite a chore. The food packaging industry, especially dairy products, offers a wide assortment of potential disposable sample containers in the larger sizes. Both the 1.91 (1/2 gal) paper and plastic milk cartons can be considered viable candidates, and their cost in quantity is in the pennys-each range.

The requirements for sample preservation were enumerated in section IV and will not be repeated here. It should be mentioned, however, that if the samples are allowed to become too cold, they may no longer be representative.

TABLE 6. RATIO OF COMPOSITE SAMPLE CONCENTRATION TO ACTUAL CONCENTRATION

q FLOW \ CONC k	$1-t$	$1-\frac{t}{2}$	$\cos\frac{\pi t}{2}$	e^{-t}	$\sin\pi t$
C	0.90 0.90 0.90 0.90	0.97 0.97 0.97 0.97	0.92 0.92 0.92 0.92	0.95 0.95 0.95 0.95	0.99 0.99 0.99 0.99
t	1.35 0.90 0.86 0.87	1.09 0.97 0.96 0.96	1.26 0.90 0.87 0.89	1.14 0.97 0.95 0.95	0.99 0.90 0.89 0.97
1-t	0.68 0.95 0.92 0.92	0.87 0.98 0.97 0.97	0.72 0.98 0.95 0.93	0.82 0.96 0.95 0.95	0.99 1.12 1.09 0.97
$\sin\pi t$	0.90 1.01 0.90 0.90	0.97 1.00 0.97 0.97	0.88 1.00 0.92 0.92	0.97 1.00 0.95 0.95	0.80 1.01 0.98 0.97

Line 1. T_cV_c - Simple composite

Line 2. T_cV_v - Volume proportional to flow rate (q)

Line 3. T_cV_v - Volume proportional to flow (Q) since last sample

Line 4. T_vV_c - Time varied to give constant ΔQ

For example destruction of the organisms necessary for the development of BOD may occur or freezing may cause serious changes in the concentration of suspended solids. Light can also affect samples and either a dark storage area or opaque containers would seem desirable. Unless disposable containers are used, however, it will be difficult to inspect an opaque container for cleanliness. Again the paper milk carton is attractive since not only is it relatively opaque, but its top opens completely allowing visual inspection of its contents.

CONTROLS AND POWER ASSESSMENT

The control aspects of some commercial automatic samplers have come under particular criticism as typified by comments in section VIII. It is no simple matter, however, to provide great flexibility in operation of a unit while at the same time avoiding all complexities in its control system. The problem is not only one of component selection but packaging as well. For instance, even though the possibility of immersion may be extremely remote in a particular installation, the corrosive highly-humid atmosphere which will, in all liklihood, be present makes sealing of control elements and electronics desirable in most instances.

The automatic sampler for storm and combined sewer application will, in all liklihood, be used in an intermittent mode; i.e. it will be idle for some period of time and activated to capture a particular meteorological event. If field experience to date is any indication, the greatest need for an improved control element is for an automatic starter. While the sensor is not a part of the sampler proper, its proper function is essential to successful sampler utilization. Although remote rain gages, etc. can be used for sensing elements, one of the most attractive techniques would be to use the liquid height (or its rate of increase) to start a sampling cycle. This will avoid the difficulties associated with different run-off times due to local conditions such as dryness of ground, etc.

One of the attributes essential to the control system of an automatic sampler to be used in a storm and/or combined sewer application is that it be able to withstand power outages and continue its program. Such power interruptions appear to be increasingly common as demand for electricity continues to grow. Although desirable in some instances, the provision of a random interrogate signal to be coupled with a sequence sample mode generates programming problems, especially when coupled with power interrupt possibilities.

Reliability of the control system can dominate the total system reliability. At the same time, this element will, in all liklihood, be the most difficult to repair and calibrate. Furthermore, environmental effects will be the most pronounced in the control system. The power switching function of the control system may be required to deal with multiple switching of inductive loads and must achieve the switching of these loads without the typical damage associated with transfer of energy interruptions.

The above tasks can probably be best executed, in the light of the current electronics state-of-the-art, by a solid state controller element. In addition to higher inherent reliability, such an approach will allow switching of high level loads in a manner that eliminates RFI emissions and destructive results. In addition, the unit should be of modular construction for ease of modification, performance monitoring, fault location, and replacement/repair. Such an approach also lends itself to encapsulation which will minimize environmental effects. Solid state switching eliminates the possibility of burned or welded contacts either of which will cause complete sampler breakdown.

Solid state controllers can be easily designed with sufficient flexibility to accept start commands from a variety of types of remote sensors, telephone circuits, etc.

Low operational current requirements would allow a solid state controller to continue to operate from a battery source during a local power outage. This capability would avoid logic interrupts and attendent loss of data and allow the sampler operation to be restored immediately upon the return of power service.

The foregoing discussion as it relates to problems associated with interruptions in electrical service is of course directed to samplers that rely upon outside power for some aspect of their operation. The need for high sample intake and transport velocities, larger sample lines and capacities, together with the possible requirement for mechanical refrigeration make it unlikely that such a sampler can be totally battery operated today. Although recent break-throughs have resulted in 1 kw dry cell batteries, their cost is prohibitive for this sort of an application. Other approaches to self-contained power such as custom designed wet cell packs, diesel generators, etc., while within the current state-of-the-art, introduce other problems and complexities that must be carefully weighed before serious consideration can be given to their incorporation in an automatic sampler design.

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16. ABSTRACT

A brief review of the characteristics of storm and combined sewer flows is given followed by a general discussion of the purposes for and requirements of a sampling program. The desirable characteristics of automatic sampling equipment are set forth and problem areas are outlined.

A compendium of 82 model classes covering over 200 models of commercially available and custom designed automatic samplers is given with descriptions and characterizations of each unit presented along with an evaluation of its suitability for a storm and/or combined sewer application.

A review of field experience with automatic sampling equipment is given covering problems encountered and lessons learned. A technical assessment of the state-of-the-art in automatic sampler technology is presented, and design guides for development of a new, improved automatic sampler for use in storm and combined sewers are given.

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